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High-Frequency Phenomena in Gases, Second Part

By KARL K. DARROW

This article on high-frequency phenomena in gases, a continuation of the one which appeared in the preceding number of this Journal, is concerned with the self-sustaining high-frequency discharges. First come the conditions for establishment of the discharge, a spark or corona if the gas-pressure is high, a glow if it is low; then, the laws of the glow-discharge when established in rarefied gas, in tubes with internal or external electrodes. The complexity of the situation is such that fundamental theory is almost powerless as yet, the article thus consisting chiefly of descriptions of data and statements of empirical laws.

THE article preceding this one was devoted principally to the things which are observed when a high-frequency electric field, generally small in amplitude, is impressed upon a gas which by some other agency is populated with electrons. The gas may be, for instance, the vehicle of a self-sustaining direct-current glow-discharge, carrying a steady current-flow between two electrodes maintained at a constant potential-difference. It will then be rich with free electrons, and also with positive ions. To a part of this host of mobile charged particles circulating among neutral atoms, the high-frequency field is applied by means of a second pair of electrodes. Or, the gas may be flooded with free electrons supplied from a heated filament, and the high-frequency force will act upon these. In all these cases of Part I, the motions which the high-frequency field imposes on the corpuscles are held accountable for the phenomena. Predictions may then be made, out of our knowledge of the behavior of free electrons wandering through gases under constant fields; and on the whole, the observations agree with the predictions to an extent decidedly satisfactory, though enough remains unexplained to encourage further study.

Those phenomena of Part I are thus the high-frequency analogues of what happens, when a weak constant electric field is applied across a gas which is ionized or flooded with free electrons by some external agent: X-rays or beta-rays or the electrons from a hot filament, for example, or a stronger field simultaneously applied in a different direction and maintaining a glow-discharge. Now if such a feeble field be gradually increased in strength, these electrons themselves take up the rôle of ionizing agents; the ionization due to the external agent is "self-amplified," as I have elsewhere said. When the field

is further strengthened, the amplification becomes more intense, the ionization more abundant, and there comes a point when the gas "breaks down." A luminous discharge occurs, which may be transitory (a spark) or durable (a glow or corona or arc). Breakdown and the subsequent discharge occur even when there is no external agent of ionization, apart from those feeble rays which constantly pervade the atmosphere and every gas not shut off from the atmosphere by heavy walls. Moreover, they occur with a high-frequency field, provided its amplitude is raised to a sufficient value. This second part of the present article is devoted to the conditions for breakdown by high-frequency fields, and the characteristics of the discharge which sets in thereafter.[12]

The discharge ensuing upon breakdown is as a rule enduring only if the gas is rarefied (to a pressure not more than a few hundredths as great as atmospheric) or one at least of the electrodes is sharply curved. Otherwise, it is a spark. Striking as is the contrast between these cases, one does well to disregard it while thinking about the processes which may lead up to breakdown, or observing the conditions under which this phenomenon occurs. What happens before the sudden transition may be controlled by laws quite other than what happens after it. Indeed, we know that the choice between spark and durable glow-discharge is not so important in principle. The choice between spark and glow is influenced, for instance, by the constants of the circuit—not merely by the E.M.F. available, but also by the resistance and inductance in series with the gas. It is advantageous, therefore, to think of the conditions for breakdown and the presumptive details of the process as forming a problem by themselves, apart from the problems of the state which follows.

General Remarks on Breakdown

Breakdown by "steady voltage" is brought about in either of two ways: by gradually increasing the voltage across a pair of electrodes separated by a stratum of gas, or by applying a fixed voltage and gradually changing the distance between the electrodes. It is detected either by the blaze of light attending the ensuing spark or glow, or by a sudden violent change in the reading of a voltage-measuring device shunted across the "gap," that is, connected across the electrodes. The figure given as the "breakdown-potential" is the last value of voltage recorded just before either of these events.

[12] The order of treatment is thus the same as is customary in treatises on direct-current phenomena, and as I have followed in my book "Electrical Phenomena in Gases," to which again reference is occasionally made: first the drifting and accelerations of electrons in gases exposed to weak fields, then the conditions for breakdown, finally the laws of the luminous discharges ensuing after breakdown. Equations, footnotes, and figures are numbered consecutively to those of Part I.

If the voltage between the electrodes is augmented rapidly instead of slowly, the breakdown-potential may be greater; it is as though the discharge were delayed for an appreciable time after the proper critical P.D. was reached, during which time the voltage is overshooting the mark and giving rise to error. I mention this because it has bearing on what follows.

If the voltage is supplied from a "source of high frequency" of one of the types customary before the development of the vacuum-tube oscillator—for instance, an induction-coil or an interrupter—it arrives as a sequence of highly-damped high-frequency wavetrains with longish intervals between. At the end of each interval, the P.D. between the plates rises suddenly and rapidly, and if it rises far enough, breakdown takes place. The difference between the rise which (were it not interrupted by breakdown) would end in the attainment of a thenceforward constant voltage, and the rise which (were it not interrupted by breakdown) would be followed by successive falls and smaller rises and alternations of direction, is practically small. True, breakdown might occur, in the latter case, during the second rise when it had missed the first; or after the completion of one damped wave-train, the gas might be left in an abnormal state lasting until the coming of the next and facilitating breakdown by the next. But this does not seem to happen in practice, and if it did, there would be obvious advantages in studying it with trains of undamped waves such as nowadays can be produced. For successions of damped wave-trains, therefore, I will merely quote the general result applicable to air at atmospheric pressure: the voltage producing sparkover, between definite electrodes at a definite distance, is almost if not quite independent of frequency up to such high values as a million cycles—what changes have been observed are generally increases and may be ascribed to the fact just mentioned, that when the voltage is increasing very rapidly it may overshoot the minimum value sufficient for sparkover before the spark gets started.

Turning now to sinusoidal wavetrains such as modern technique makes available: if such a one be applied while its amplitude is yet too small to cause a breakdown, and then the amplitude is gradually increased (or alternatively, the distance between the electrodes is diminished) it will gradually modify the gas by reproducing ionization in ever-increasing amount—the "self-amplifying" effect of the ionization, which I mentioned above; and this will eventually bring about breakdown. We know a great deal about this preliminary process for steady voltages, but as yet we can only infer it for alternating voltages. Thus for steady voltages, there must be at least two modes of ioniza-

tion: the well-known action of free electrons striking molecules of the gas, and a complementary process, which may (for instance) be the ejection of fresh electrons from the cathode by positive ions striking that electrode.[13] Were it not for the latter process (or some other) the direct-current discharge could never develop; for though at a given instant there might be some electrons in the gas, they and all the other electrons which they might liberate would steadily drift off toward the anode, and ionization and current-flow would cease after all of them had reached it. Now if the voltage is oscillating instead of constant, the electrons in the gas may rush to and fro and ionize all parts of it, and the importance of the complementary process will be reduced; though it can never be annulled, since the electrons will sooner or later get to the anode or the walls, and must be replenished from the cathode.

Again, we know that a factor in the advent of breakdown by a steady voltage is the distortion of the field in the gas by space-charge, which arises chiefly near the cathode, because the positive ions formed there by electron-impact drift only slowly toward the cathode while the electrons which should balance their charge drift rapidly off toward the anode. If the voltage is oscillating there will also be a positive space-charge due, in the last analysis, to the fact that electrons drift faster than positive ions; but it will be distributed symmetrically about the middle of the gap.

These remarks may have given the impression that the differences between breakdown at high frequencies and breakdown by steady voltage have been successfully explained. As a matter of fact, there is no quantitative explanation, and I have little to say except to present the data.

Breakdown of Air at Atmospheric Pressure

For air at atmospheric pressure, for which breakdown is sparkover unless one or both of the electrodes be sharply curved, the latest data are those of Lassen.

Curves of sparking-potential versus distance, (V_s-vs-d curves), obtained with spherical electrodes of 2.5-cm. diameter, over the range of distances from 0.05 to 0.5 cm., appear in Fig. 12. The voltage was adjusted to a chosen value, and the distance gradually lessened until sparkover occurred. The straight line is fitted to the points obtained with frequency $1.1 \cdot 10^6$ and the points obtained with frequency 50. Fifty-cycle A.C. is practically the same, with regard to the processes

[13] "Electrical Phenomena in Gases," pp. 280–297.

leading up to breakdown, as steady voltage; these data therefore indicate that up at least to frequencies of the order of a hundred thousand, an oscillating voltage causes breakdown when its amplitude becomes the same as the steady voltage which can have the like effect; and this is in agreement with other observations.

The curves which depart from the straight line correspond to

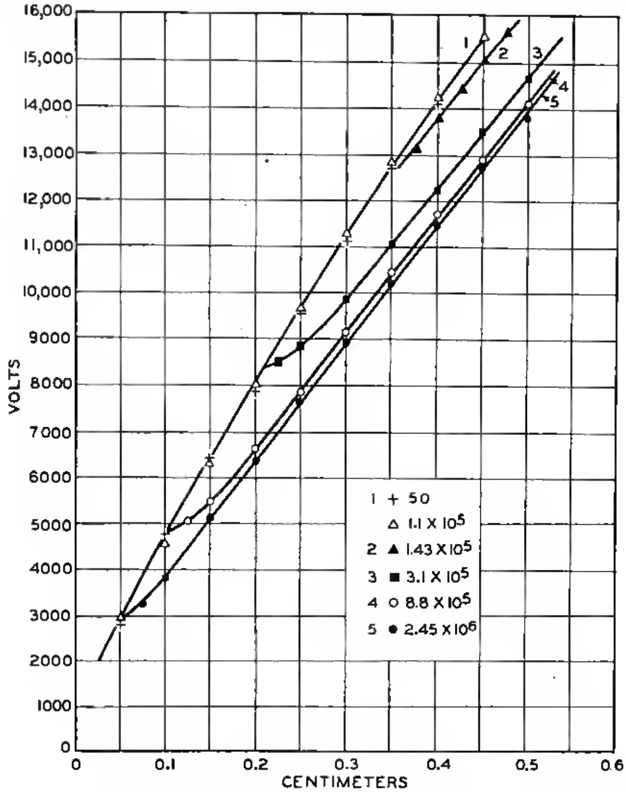

Fig. 12—Curves of sparking-potential versus distance, in atmospheric air, between spherical electrodes of 2.5-cm. diameter, at various frequencies. (Lassen, *Arch. f. Elektrotech.*)

various higher frequencies, indicated on the figure. The "critical distance" at which the departure occurs is inversely proportional to the 2/3 power of the frequency. If the data are plotted differently, sparking-potential versus frequency for the various gap-widths, each curve is parallel to the axis of abscissæ up to a "critical frequency" which increases with decrease of distance (Fig. 13). Beyond the critical frequency, each curve drops off, the ordinate sinking by fifteen to

twenty per cent. On Lassen's curves (hollow circles of Fig. 13), there are indications that beyond the drop the curve again becomes horizontal; these are borne out by curves earlier obtained by Reukema with 6.25-cm. spheres (black dots of Fig. 13), although there are clashes between the two sets of data which may or may not be entirely due to the difference in the sizes of the spheres.

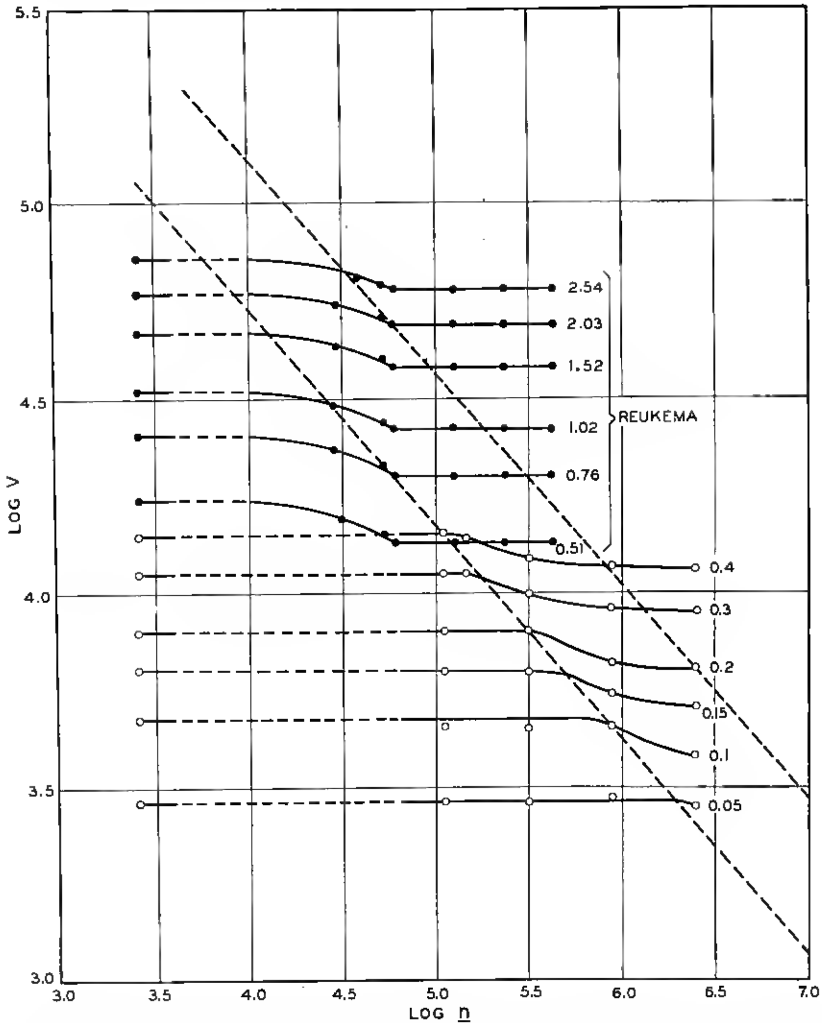

Fig. 13—Curves of sparking-potential vs. frequency, in atmospheric air, between spherical electrodes. (Data from Lassen and Reukema; the various curves correspond to the indicated gap-widths.)

The data which I have thus far cited pertain to gap-widths considerably smaller than the radii of curvature of the electrodes: fairly close approximations to the extreme case of infinite parallel planes. Experience with steady voltages suggests that what really counts is probably not the absolute value of gap-width, but its ratio to the radii of curvature (or to the smaller of the two, if the electrodes are not alike). The foregoing data then show that as this ratio increases, there is a diminution of breakdown-voltage at the higher frequencies,

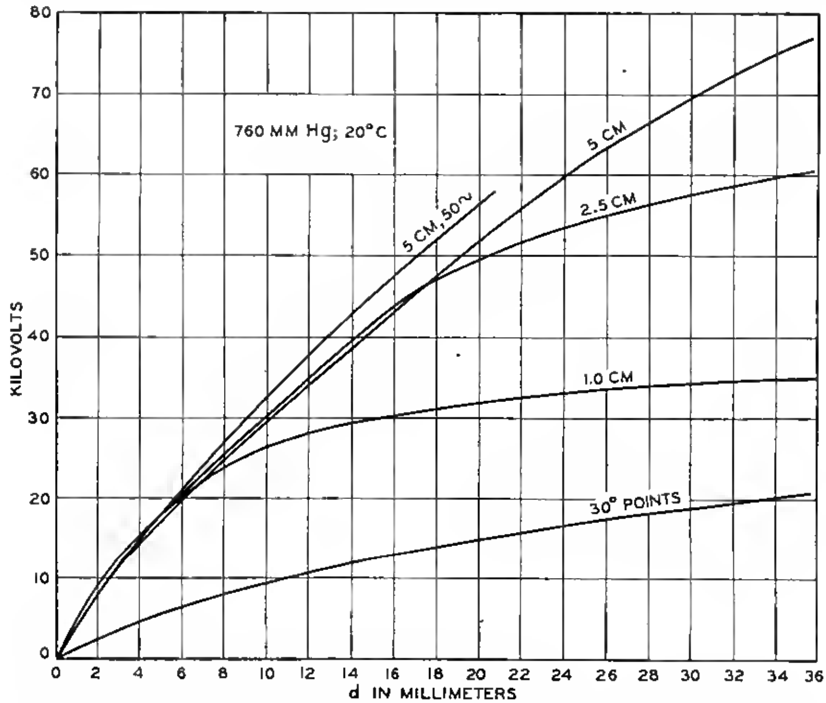

Fig. 14—Curves of sparking-potential vs. gap-width, in air, between spherical electrodes of the indicated radii, at frequencies of the order 10^5 (except the topmost). (Kampschulte, *Arch. f. Elektrotech.*)

setting in earlier the larger the ratio is. Continuing in this line of thought, we infer that as we approach the opposite extreme case of sharply-curved or pointed electrodes at distances many times as great as their radii of curvature, the diminution will begin at very low frequencies and will be considerable.

This occurs, and is illustrated by Figs. 14 and 15 (from Kampschulte) the former of which shows the breakdown-potentials between spheres of the indicated radii, over the range of distances indicated along the

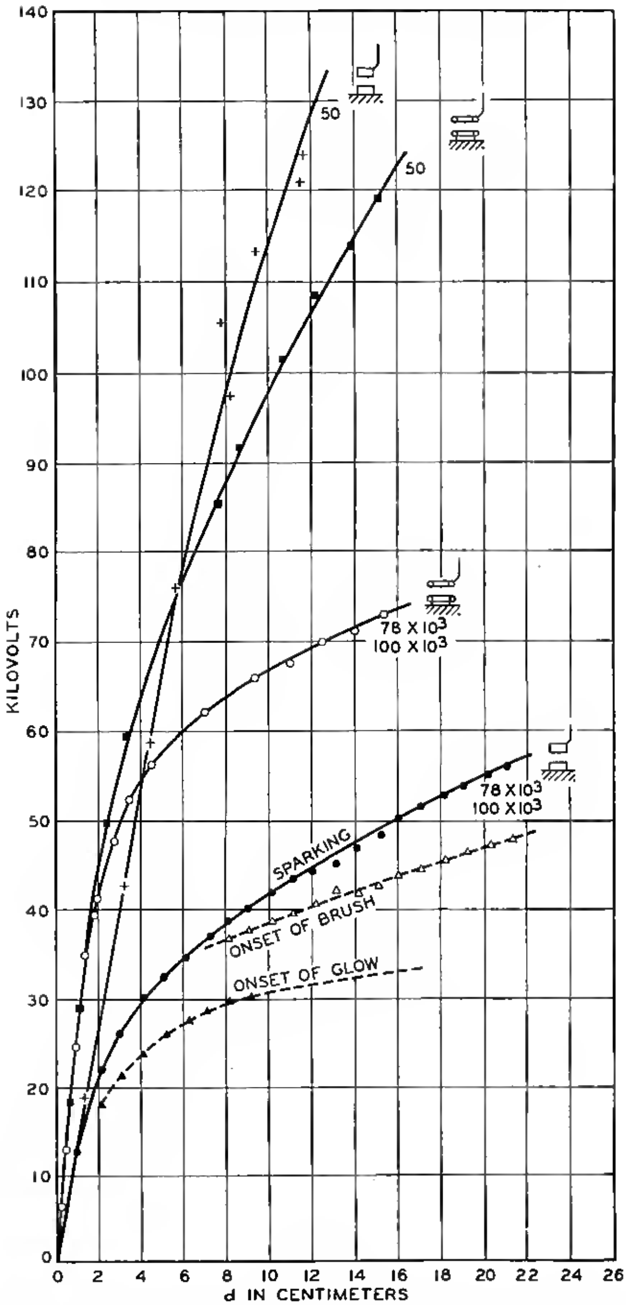

Fig. 15—Breakdown-potentials vs. gapwidth, in air, at the frequencies indicated, for the kinds of electrodes sketched in the figure and described in the text. (Kampschulte.)

axis of abscissæ. The common frequency is 73 or 107 kilocycles (Kampschulte seems to have found no difference between the behavior of the two), except for the curve marked "50 cycles" which as before may be regarded as the curve for steady voltage. The lowest of the curves pertains to electrodes sharpened at their ends to cones, with an angle of 30° at their points.

Fig. 15 is still more interesting, although the data were obtained with electrodes of a curious and inconvenient shape—collars or rings of metal, sometimes with sharp edges and sometimes with rounded edges, as the little sketches beside the curves suggest. Even for the blunt-edged electrodes the breakdown occurs at notably lower voltages for frequencies of the order of one hundred thousand than for 50-cycle or steady voltage, unless the gap-width is small. For the sharp-edged electrodes the difference is still more striking.

Most interesting of all is the triad of curves at the bottom of Fig. 15. If the gap-width between the sharp-edged electrodes is set (for instance) at 10 cm., and voltage of frequency 10^5 is applied and gradually increased, three transitions follow one after another: first, the establishment of a durable self-sustaining discharge of a certain aspect; then, its sudden transformation into another durable self-sustaining discharge of visibly different aspect; lastly, the advent of the spark. The first transition may be regarded as the breakdown of the initially undisturbed gas; the second, as the breakdown of the gas when ionized in the peculiar way prevailing in the first of the self-sustaining discharges; the third, correspondingly. With steady voltage likewise, sparkover is anticipated by the onset of a durable self-sustaining discharge if the ratio of gap-width to radius-of-curvature of one electrode is sufficiently high.[14] For the fifty-cycle A.C. applied to the sharp-edged electrodes, Kampschulte displays in Fig. 15 only the curve for sparkover; but he implies in the text that the other two discharges were observed to precede the spark.

Accurate explanation of these laws is lacking. The most that has been achieved is a rough test of a certain rough inference from theory.

Say that we establish a certain gap-width: determine the sparking-potential with steady or low-frequency A.C. voltage; and then apply

[14] "Electrical Phenomena in Gases," pp. 301–303, 443–445; note Fig. 64 on page 302 (taken from F. W. Peek, Jr., "Dielectric Phenomena in High-Voltage Engineering") which shows the critical potentials for the durable discharge or "corona" dropping below that for sparkover at a certain value of the ratio of gap-width to radius. The terms "*Glimm*" and "*Bürsten*" used by Kampschulte would be translated literally as "glow" and "brush," but usage in English is so uncertain that I have done so with hesitation.

to the electrodes potential-differences of successively higher and higher frequencies, with a certain constant peak value just inferior to the sparking-potential aforesaid. Electrons and positive ions will both oscillate in the field. For their oscillations, two sets of equations were written down in Part I: one for the extreme case of vacuum, the other for the opposite extreme case in which the collisions of the electrons with atoms are very numerous in a single cycle of the voltage. It is the latter extreme which fits more closely the present case of air at atmospheric pressure. I repeat from Part I the equation (there numbered 9) for the amplitude A of vibration of an ion of which the mobility is represented by μ:

$$A = \mu e/2\pi\nu. \tag{27}$$

The value is much greater for the electrons (because of their greater mobility) than for the positive ions.[16] At low frequencies this matters little, for both amplitudes are much greater than the gap-width and nearly all particles of both kinds are swept to the electrodes. As the frequency is raised, however, we eventually reach a point at which the amplitude of oscillation of the positive ions is depressed below the amount of the gap-width; many will then remain in the gas during cycle after cycle of the voltage while the electrons, as previously, will mostly be cleared out during the cycle in which they are formed. The effect of the positive ions in distorting the field by their space-charge will then be enhanced; the "rough inference" aforesaid is that on this account (or on some other) the breakdown-voltage will then be appreciably diminished.

To test the inference, one should measure the breakdown-voltage and compute the corresponding fieldstrength, at or near the "critical frequency" where the diminution begins; and into equation (27) one should insert the value μE for the drift-speed of the positive ions at the said fieldstrength, and for the amplitude A one should put the gap-width; and compare the resulting value of ν with the observed critical frequency. One is then baffled by the lack of measurements of drift-speed at such high fieldstrengths (the imminence of breakdown makes the customary methods of measurement difficult if not impossible). For this and other reasons, no more than an order-of-magnitude agreement is to be expected; and such a one is attained. Thus in

[16] This statement remains valid, despite the fact that (27) is probably not applicable to free electrons. It is based on the assumption that drift-speed is proportional to fieldstrength, *i.e.* that the mean kinetic energy of random motion of the electrons is independent of the field; this is certainly not true for electrons in a steady field, probably not in a high-frequency field. For positive ions it is true for low fieldstrengths, but should depart somewhat from exactness as the field is raised toward the value prevailing just before breakdown.

Lassen's experiments, the fieldstrength E at breakdown is about 30 kv./cm., for every gap-width between 0.3 and 2 cm.; if for the drift-speed of positive ions at this fieldstrength one puts 10^5, and for the amplitude of the oscillations puts the amount of the gap-width, one gets 10^6 for the critical frequency at gap-width 0.3 mm., and this —as Fig. 13 displays—is the proper order of magnitude. A like agreement is obtained with Reukema's data. But the values postulated for the drift speeds are scarcely more than guesses (in Lassen's case it is assumed that the mobility at 30 kv./cm. is two and a half times what it is at one volt per cm.); and plausible as the theory seems, the experiments help it but little.

On the other hand, observations have been made on the number of ions formed by an electron on its way across air at atmospheric pressure, at fieldstrengths of the order of those existing in these experiments.[16] This is an exponential function of E, and small variations of E thus make enormous differences in it. Lassen figures that just before breakdown at frequency $2.45 \cdot 10^6$, an electron crossing the gap (of any width between 0.2 and 2 cm.) produces 36 ion-pairs, while just before breakdown at constant voltage it would produce no fewer than ten million. This is a striking result.

Breakdown-Potentials in Gases at Low Pressures

Breakdown across a stratum of gas of low density—that is to say, having a pressure of a few millimeters of mercury, or a few tenths or a few hundredths of a millimeter—is normally followed by the establishment of a durable self-sustaining discharge, oftenest of the type called "glow." This rule, which for a gas at atmospheric pressure prevails only if one at least of the electrodes is so much rounded that its radius of curvature is decidedly smaller than the gap-width, is not thus limited at those lower densities. For an obvious reason, the rarefied gas is always confined within a tube, which in most of the experiments with high frequencies (those on the ring-discharge excepted) is a cylinder only a few centimeters wide; thus, to judge from experience with direct-current discharges, the presence of the wall must have a great influence on the phenomena. The electrodes are commonly either discs inside the tube near its ends, or belts of tinfoil wrapped around the outside of the tube; at high frequencies it often makes surprisingly little difference which, and yet such differences as have been reported are sometimes noteworthy. Breakdown-potentials are generally determined by raising the amplitude of the high-frequency

[16] M. Paavola, *Arch. f. Elektrotechnik*, **22**, 443–458 (1929); "Electrical Phenomena in Gases," p. 278.

voltage gradually till suddenly a visible discharge appears; the last previous reading of the voltage is then recorded. Some physicists have reported that the advent of the self-sustaining glow is difficult to observe, or capricious and unreproducible; others mention nothing of the sort.

There are now two independent variables, frequency and pressure, instead of the former only; this makes it harder to view the data. So long as the frequency is held constant, the curve of breakdown-potential versus pressure usually has the familiar form, characteristic of steady as well as alternating voltages: it is concave upward, with a single minimum, perhaps deep and striking, perhaps so flat as scarcely to be visible. There is consequently for each frequency an optimum pressure, P_{sm} say, for the onset of the glow; at pressures either lower or higher than P_{sm}, the critical potential is above its minimum value V_{sm}. In general terms, the reason is this: at high pressures, ionization is restricted by the fact that in their numerous collisions, the electrons lose energy so often that they seldom amass enough to ionize the molecules—at low pressures, it is restricted by the fact that there are few collisions—at the intermediate pressure P_{sm}, the best compromise prevails between the two disadvantages. There can be little doubt that if one were to vary the distance between the electrodes in lieu of the pressure, the effect would be the same, according to Paschen's law that breakdown-potentials depend on the product of pressure and distance.[17]

When one compares the breakdown-potential versus pressure or V_s-vs-p curves for various frequencies, the results are often far from simple, and different observations are sometimes hard to reconcile; even when one considers only undamped sinusoidal wavetrains, as I shall do.

Thus Hulburt, working with oxygen and hydrogen at pressures of 1 to 5 mm., in tubes with internal electrodes 5 to 30 mm. apart, experimented with steady voltages, with 50-cycle A.C., and with the high frequencies $0.86 \cdot 10^6$ and $5.3 \cdot 10^6$; and he detected *no* variation of the voltage for the onset of the glow over all this range. Likewise Rohde, working with a number of gases (oxygen, hydrogen, nitrogen, argon, neon, helium, mercury) in tubes with electrodes (usually internal) 19 or 38 mm. apart, applied frequencies ranging from 10^5 to $1.5 \cdot 10^8$. Up to about 10^6 the breakdown-voltage scarcely changes; thence-

[17] "Electrical Phenomena in Gases," pp. 304–308. Paschen's law in this form is valid only for broad plane-parallel electrodes; to make it hold for curved electrodes, their radii of curvature should be varied in the direct ratio of the distance or the inverse ratio of the pressure.

forward it declines.[18] In Fig. 16 I show three of his V_s-vs-p curves for oxygen, in a tube with electrodes 38 mm. apart; they correspond to wave-lengths 9.8, 5.03, 4.32 metres, therefore to frequencies $3.1 \cdot 10^7$, $6 \cdot 10^7$, $7 \cdot 10^7$. It is obvious that for any pressure in the range of these experiments, V_s diminishes as ν increases; also, that p_{sm} as well as V_{sm} diminish with increasing frequency.

From Townsend's school at Oxford, I will quote some observations of Hayman on helium and neon at pressures ranging from a few mm. to a few tenths of a mm., in cylindrical tubes with external collar electrodes. A curve of V_s-vs-p for frequency $3.75 \cdot 10^6$ displays a

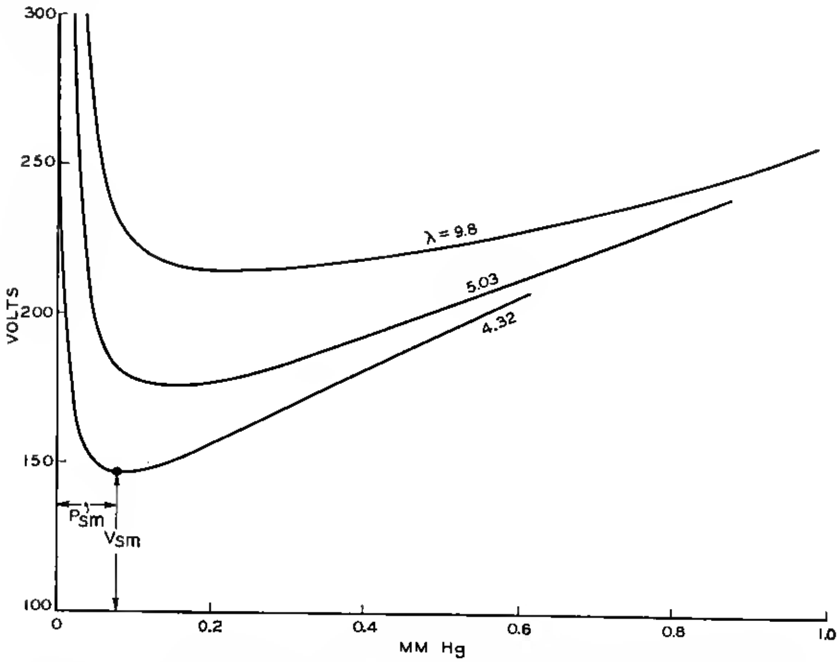

Fig. 16—Onset-potential vs. pressure, in rarefied oxygen, for self-sustaining glow-discharge at the indicated wave-lengths of the high-frequency voltage. (Rohde, *Ann. d. Phys.*)

minimum. Curves of V_s-vs-ν slope downwards toward higher frequencies over the range from $4.7 \cdot 10^5$ to $7.5 \cdot 10^6$, the slope being gentle at pressures above 2 mm. and very rapid at pressures rather lower (at 0.11 mm. there is a drop in a ratio greater than 6 : 1, as the frequency is raised from the bottom to the top of the aforesaid interval).

[18] Rohde devotes so much of his attention to the maintaining-potentials (see below) that his allusions to the onset-potential are scanty, and their degree of generality is hard to assess.

In a narrow tube, a greater voltage is required for breakdown than in a broad one—at pressure 1 mm., twice as great a voltage for a 1.5-cm. tube as for one of 3.9-cm. diameter. This last is an illustration of the effect of the walls; probably they influence the preliminaries to breakdown by capturing and retaining the electrons which approach them from the gas, so that the ionizing agencies at work in the gas must be strengthened to compensate that loss. Townsend and Nethercot also record a V_s-vs-p curve with a minimum, for frequency $7.5 \cdot 10^6$.

If one knew only of the foregoing papers, one would resume the situation as follows: for any value of pressure, breakdown-potential diminishes steadily with increase of frequency, but the diminution is

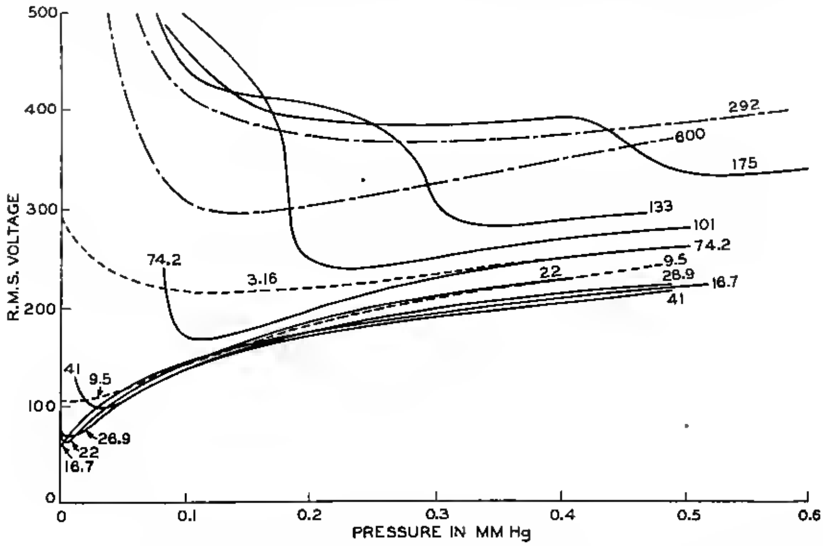

Fig. 17—Onset-potential vs. pressure, in rarefied hydrogen, for self-sustaining glow at the indicated wave-lengths. (H. Gutton, *Annales de Physique.*)

very small all the way from $\nu = 0$ to $\nu = 10^6$; for any value of frequency, the curve of V_s-vs-p has a single minimum; the coordinates p_{sm} and V_{sm} of that minimum decrease with increasing ν. There would be wide gaps in the range of frequency over which these statements had been tested, but nothing would suggest that there might be discrepancies within the gaps. However, the situation is not so simple. Mention must be made of remarkable and perplexing data obtained by C. and H. Gutton and collaborators of theirs, mainly with external-electrode tubes.

Fig. 17, relating to hydrogen, is taken from some of H. Gutton's

most recent work: it is a set of V_s-vs-p curves for various frequencies of an extremely wide range (the wave-lengths in meters are marked beside the curves) obtained with a tube 10 cm. long closed at its ends by flat plates, covered outwardly by sheets of tinfoil serving as the electrodes. (Gutton never indicates the actual observations on his graphs.) It is superfluous to say that this family of curves is easy neither to envisage nor to describe. Most of them are of the type

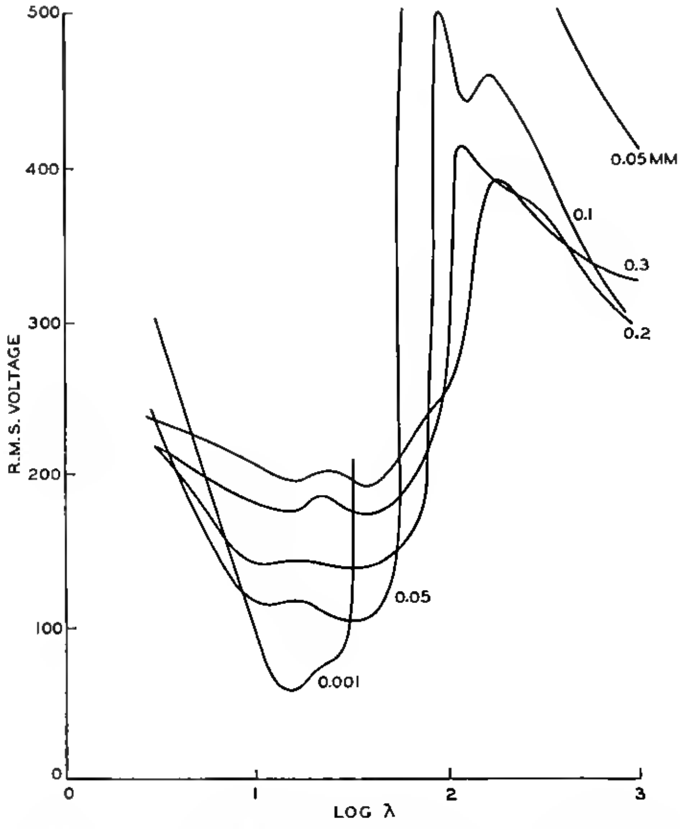

Fig. 18—Onset-potential vs. (logarithm of) wave-length, for self-sustaining glow at the indicated pressures. (H. Gutton.)

familiar from other researches, with a single flattish minimum; but some are very different, with no minimum at all in the range of experiment, but a couple of sharp bends with a linear segment between. The V_s-vs-ν curves for various pressures, exhibited in Fig. 18, form a set even more confusing.

Over the frequency-ranges where the curves of Fig. 17 have single

minima, where accordingly we may define V_{sm} and p_{sm} as before, these do not always vary in the same sense with ν. As the frequency is raised from about $4 \cdot 10^5$, V_{sm} increases at first; then come the curves with curious shapes; when again the flattish minima return, at $4 \cdot 10^6$ cycles or thereabouts, V_{sm} is following the hitherto-familiar rule of decreasing with increase of frequency; but further along, beyond about $3 \cdot 10^7$, the trend again reverses, and V_{sm} rises once more. There is thus an "optimum frequency," at which (for a wide range of pres-

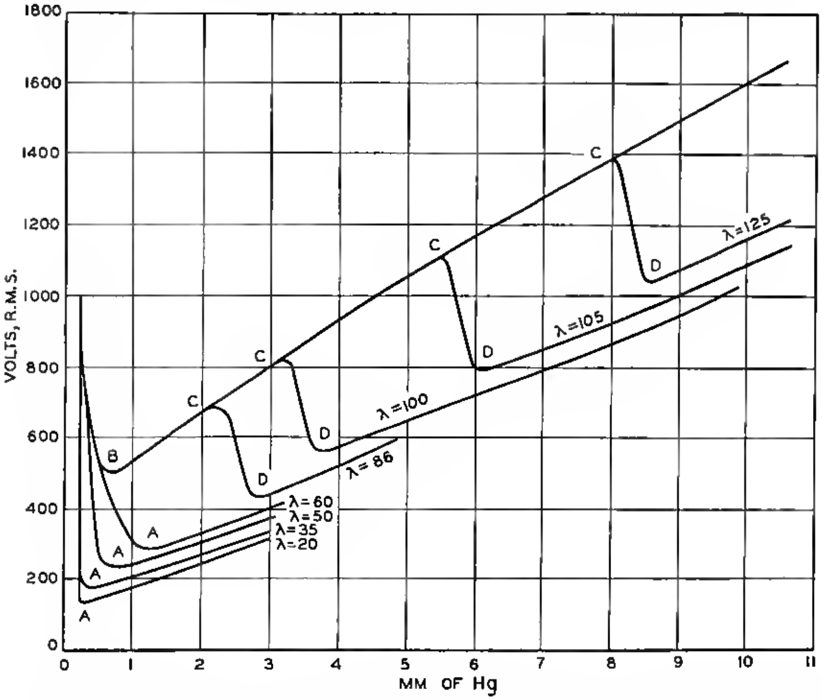

Fig. 19—Onset-potential vs. pressure, in rarefied air, for self-sustaining glow at the indicated wave-lengths, in tube described in context. (Gill & Donaldson, *Phil. Mag.*)

sure) breakdown occurs at a lower voltage than when ν is either lower or higher. This comes at about $3 \cdot 10^7$ cycles for tubes 10 to 20 cm. long, lower down for a 5-cm. tube.

These complexities far surpass what other observers report. The others, it is true, confined themselves to narrower ranges of frequency, and yet their ranges were often so located on the frequency-scale that they should have observed some of the striking reversals of trend and distortions of curves, had the conditions been the same; to seemingly

minor differences in the conditions, then, the discrepancies must be ascribed. The complexities are not peculiar to hydrogen, for Gutton obtained a very similar set of curves with oxygen, and in much earlier work (1923) on rarefied air he found V_{sm} increasing with frequency up to about $7.5 \cdot 10^5$ cycles, and thenceforward diminishing all the way to the uppermost limit of his frequency-range, $2.14 \cdot 10^6$. This last-mentioned result was obtained with an external-electrode tube, the exterior tinfoil belts 24 mm. apart; on substituting an internal-electrode tube, he found V_{sm} increasing with ν over the entire frequency-range. But I must leave the reader to explore and collate Gutton's numerous curves for himself, and mention only in closing that in a tube of rarefied hydrogen with external electrodes 53 mm. apart, he got at frequency $2.5 \cdot 10^7$ a breakdown-potential of only 57 volts—an amazingly small value, far lower than anything ever obtained with direct current.

Gill and Donaldson produced V_s-vs-p curves with two minima apiece instead of one, by placing the long slender discharge-tube (20 cm. long, 3.3 cm. diameter) between two metal plates serving as the electrodes, with its axis parallel to their planes. These curves were obtained in rarefied air, with various frequencies between $3.5 \cdot 10^6$ and $2.3 \cdot 10^6$, corresponding to wave-lengths between 86 and 125 meters; one sees them in Fig. 19. (Below and to the left are curves for four other and higher frequencies, ranging from $5 \cdot 10^6$ to $1.5 \cdot 10^7$; these have the familiar single-minimum controur, and both V_{sm} and p_{sm} decrease as ν increases.) Thereupon, Gill and Donaldson re-oriented the tube so that its axis was perpendicular to the electrode-plates—owing to its length, it had to be passed through a pair of holes made specially in the plates—and repeated the observations. Now, of the two minima, the one to the right disappeared; for each of the several wave-lengths, the curve continued straight on past the point marked D in Fig. 8, to a single minimum lying far to the left.

Maintaining-Potentials of High-Frequency Glows in Rarefied Gases

When the high-frequency glow in a rarefied gas is established, the voltage between the electrodes—that is to say, the amplitude V of the oscillating voltage—is as a rule much smaller than the breakdown-potential. It would seem natural to begin the study of the glow by determining the curves of current versus voltage and current versus length (*i.e.* anode-to-cathode distance) for many values of pressure, as the custom is in dealing with direct-current discharges; but data of this sort are few. Further along I will speak of work of Townsend's

school, in which over a limited range of conditions V was found to be almost independent of i (the amplitude of the oscillating current) and a linear function of the length l. Also Hayman speaks of observing a minimum in the curve of V versus i, occurring "at a value of current slightly greater than the least which gives a uniform glow in the tube." Often, however, the experimenters simply vary the strength of the oscillating current (usually by varying the filament-current of the vacuum-tube oscillator, which is coupled to the circuit containing the discharge-tube) and measure the voltage across the electrodes just before the glow disappears. This is called the "least maintaining-potential" or the "extinction-potential" or by some equivalent name. By analogy with direct-current discharges, it should depend on the constants of the circuit.

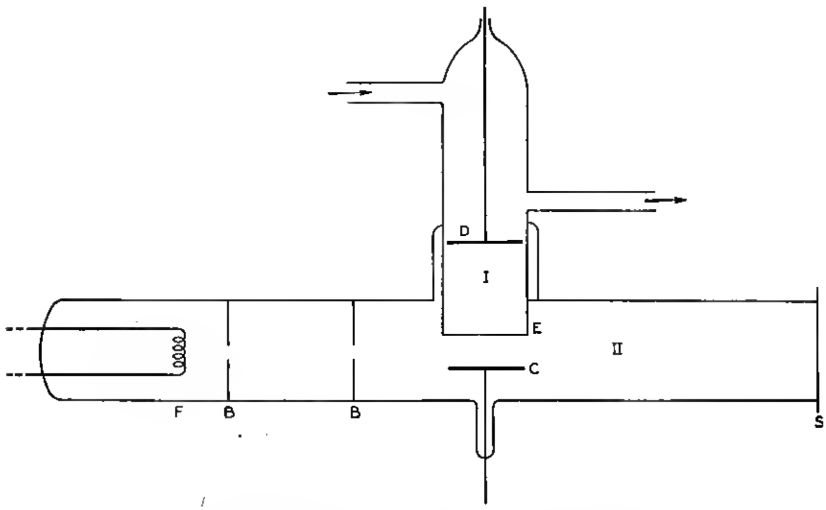

Fig. 20—Kirchner's apparatus for measuring amplitude of voltage in high-frequency glow-discharge. (Kirchner, *Ann. d. Phys.*)

The researches of Kirchner and of Rohde cover between them the widest variety of gases and the broadest range of conditions: in respect of frequency, the former worked over the range from 1.2 to $3.5 \cdot 10^7$, the latter from $3.1 \cdot 10^7$ to $1.39 \cdot 10^8$. Kirchner's method of measuring voltage deserves especial mention. Its principle is that of the cathode-ray oscillograph: a beam of fast electrons is deflected to and fro by the P.D. applied between two plates, one on either side of the beam. These could be the electrodes, but that the fast electrons might then perturb and be perturbed by the discharge, and there would be other disadvantages. Kirchner therefore designed three

pieces of apparatus, of which one is figured in Fig. 20. The discharge is in the tube I, between the electrodes D and E, of which the latter is a sheet of metal separating I from the evacuated tube II; the beam of fast electrons, proceeding from the filament F and formed by the diaphragms B, passes between E and the lower plate C which is constantly at the same potential with D. The voltage between C and E is the same as that between the electrodes of the discharge; the measure of its amplitude is the length of the arc which the tip

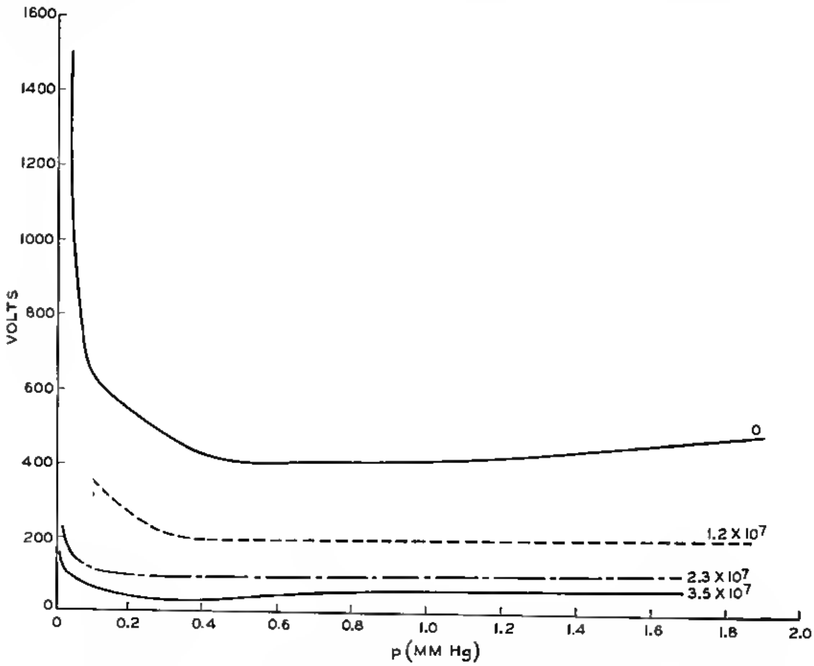

Fig. 21—Least maintaining-potential vs. pressure, in rarefied air, at the indicated frequencies. (Kirchner.)

of the beam describes, as it dashes back and forth over the surface of S, a fluorescent screen.

Mostly the curves of least maintaining-potential versus pressure, like those of onset-potential versus pressure, are concave-upward with single flattish minima. Fig. 21 shows four curves which Kirchner obtained with air. They are not very smooth nor are the minima clearly marked; I choose them for reproduction because they comprise a curve for direct-current discharge (marked 0) as well as three others for certain high frequencies marked beside them.

Let me denote by V_{mm} and p_{mm} the coordinates of the minimum of

such a curve as those of Fig. 10, and call V_{mm} the "minimum of the least maintaining potential" or simply the "minimum maintaining potential" for the frequency in question (we must choose between lengthiness and lack of precision in our terms!). The value of p_{mm} and the value of V_{mm} both decrease with increase of ν, after the variation begins; consequently, a curve of V_{mm} vs ν, such as we will now consider, corresponds not to a single pressure but to as many different pressures as there are points.[19] Disregarding this complication, notice the curve of Fig. 22.

This is the curve of minimum maintaining-potential versus frequency for air in a tube of 24 mm. internal diameter, with electrodes 19 mm. apart. It is taken from Rohde, who says that the curves for oxygen,

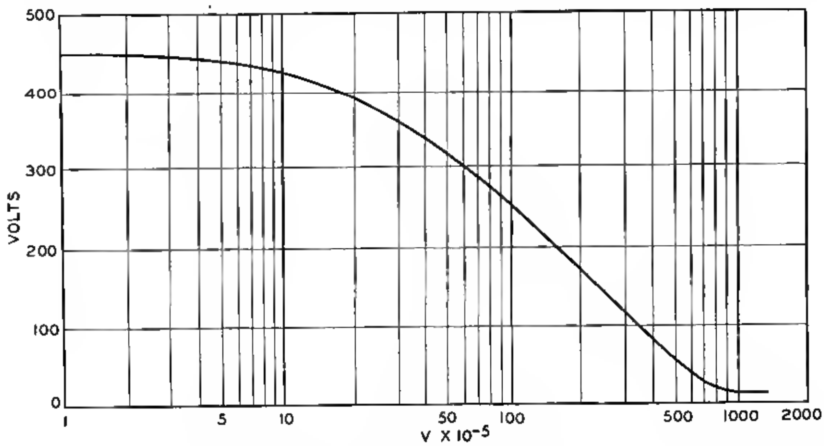

Fig. 22—Minimum maintaining-potential vs. frequency, in air, under conditions described in the context. (Rohde.)

nitrogen, hydrogen, helium, neon and argon are similar. The comparative constancy of V_{mm} at frequencies below about half a million, the rapid decline thenceforward as far almost as 10^8, are evident. Beyond, there is a definite hint that the voltage again becomes independent of ν, at a value far lower than its low-frequency or direct-current amount; for each of the aforesaid gases, hydrogen alone excepted, V_{mm} was sensibly the same at $1.39 \cdot 10^8$ (Rohde's highest frequency) as at $6.95 \cdot 10^7$.

One is struck by the resemblance to what Reukema and Lassen observed of the sparking-potential across atmospheric air: approximate constancy up to a certain critical frequency, ensuing decline, eventual

[19] The only extensive set of published curves of V_m-vs-ν is that of H. Gutton, which is more complex than one would expect (see below).

attainment of another and much lower constant value. There the critical frequency was found to depend on the gap-width and on the curvature of the electrodes; here, the data are too scanty to permit of a similar, or any conclusion. The behavior of the breakdown-potential V_{sm} in these tubes of rarefied air is of the same sort but (according to Rohde) the percentage-drop from its low-frequency value to its value at the highest frequency attained is much less striking than that of the minimum maintaining potential V_{mm}. The ratio of V_{mm} to V_{sm} therefore decreases with increase of ν, descending for argon to the value 0.1, for mercury to the fantastically low value 0.036.

The smallness of these lowest values of the maintaining potential is something extraordinary. They are, of course, much smaller than the minimum maintaining potential of the direct-current glow, which is the cathode-fall, and is of the order of hundreds of volts. Now, the office of the cathode-fall is to maintain the outflow of electrons from the cathode (this is proved by the fact, among others, that it becomes dispensable if the cathode is heated to such a degree that the outflow becomes spontaneous). The conclusion therefore is, that in the high-frequency discharge the demand for electrons from the electrodes is minimized if not abolished. Even so, the minuteness of the voltage-amplitudes remains astonishing. Taking Rohde's data for the frequency of 10^8, and going from the least toward the most striking case, we notice: air 14 volts, oxygen 12, nitrogen 12.5, hydrogen 15.5, helium 16, neon 11, argon 8, mercury 5 volts. I illustrate this by Rohde's curve (Fig. 23) of maintaining-potential versus pressure for neon, though in one respect the curve is quite untypical: no other gas exhibits so long a nearly horizontal arc (in a tube of 24 mm. diameter, and 19 mm. from one to the other of the electrodes).

More striking yet are some of the values obtained by C. and H. Gutton, whose flock of curves of V_m-vs-p for various frequencies and V_m-vs-ν for various pressures, obtained in long tubes with rarefied hydrogen within and metal electrodes outside, is almost as intricate and perplexing as the family of curves for the breakdown-potential of which I spoke above. Many indeed exhibit no minimum at all. However, with a tube 5.3 cm. long he maintained the discharge, at some $4 \cdot 10^7$ cycles, with a voltage of amplitude 5.7; and with a twenty-centimeter tube at $2 \cdot 10^7$ cycles he kept it alive with a voltage amplitude of 40, which considering the length is almost equally remarkable.[20]

[20] In consulting papers of the Guttons, remember that they give R.M.S. values of voltage and fieldstrength, not peak-values nor amplitudes.

One instinctively compares these values with the ionizing and resonance potentials of the gases, and finds them mostly lower. But actually there is no sense in making such a comparison, and indeed it is difficult to derive from theory anything with which they may profitably be compared. The most that one can do is to attempt to estimate the maximum kinetic energy which electrons should possess, not after having fallen through a constant potential-drop of the stated magnitude, but while they are under the influence of an oscillating fieldstrength of the corresponding amplitude.

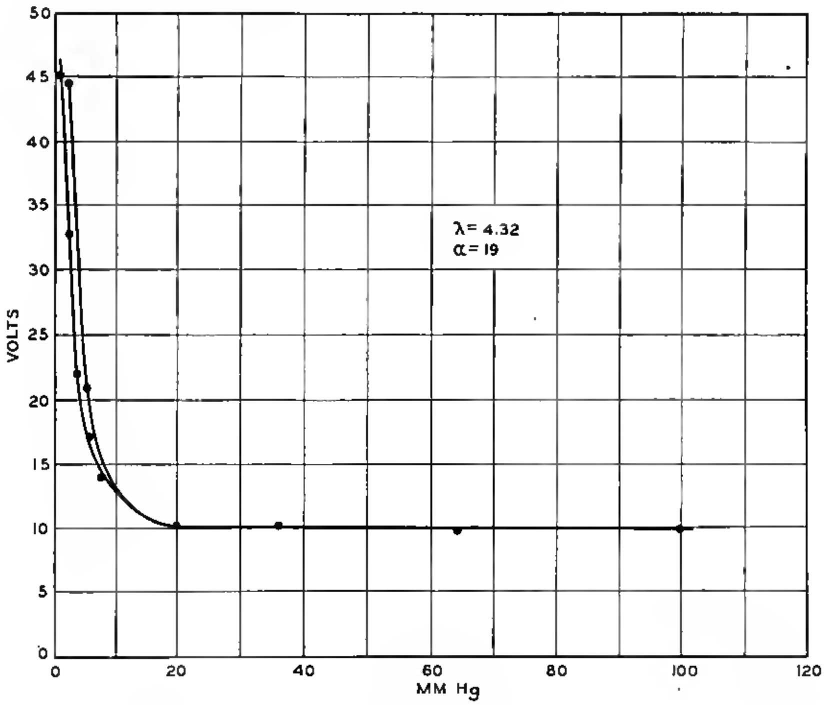

Fig. 23—Least maintaining-potential vs. pressure in rarefied neon at frequency $7 \cdot 10^7$. (Rohde.)

The formula required was given in equation (4) of Part I, but on examining it, one sees that it involves an unknowable quantity. Say that the fieldstrength is directed along the axis of x, and is given by the expression $eE \sin(2\pi\nu t)$, so that it is zero at $t = 0$ and positive immediately after; then this unknowable quantity, denoted by v_0, is the component along the x-axis of the velocity of the electron at $t = 0$. Indeed, there is a second unknowable, the component normal

to the x-axis; call it v_n. For K_m, the maximum kinetic energy of the electron, we then have (repeating equation 4):

$$K_m = \frac{1}{2} m \left[\left(v_0 + \frac{1}{\pi\nu} \frac{eE}{m} \right)^2 + v_n^2 \right] \tag{28}$$

and one sees that it is idle to assign an exact maximum value to the energy of the free electrons roaming in a vacuum subjected to a high-frequency field, since we cannot possibly know the initial velocity-components v_0 and v_n of all these corpuscles at the instant $t = 0$.

If we do the easiest thing, and simply put $v_0 = 0$, we get for K_m the expression:

$$K_m = \frac{1}{2} m \left(\frac{1}{\pi\nu} \frac{eE}{m} \right)^2. \tag{29}$$

Here, of course, energy and fieldstrength are expressed in electrostatic units. Putting them in electron-volts and volts-per-cm. respectively, and denoting them by K_{mv} and E_v respectively to symbolize this choice of units, we obtain:

$$K_{mv} = \frac{10^8 e}{2m\pi^2 c} \left(\frac{E_v}{\nu} \right)^2 \tag{30}$$

$$= 8.95 \cdot 10^{13} \left(\frac{E_v}{\nu} \right)^2. \tag{31}$$

I recall from Part I that this choice of value for v_0, like every other except one, leads to the result that the electron oscillates not about a fixed but about a drifting centre. The solitary choice which results in the electron vibrating about a stationary centre,—to wit,

$$v_0 = - eE/2\pi\nu m \tag{32}$$

—produces for the maximum kinetic energy a value one-fourth as great as that given by equation (31).[21]

On inserting into equation (31) the various frequencies at which experiments have been made, and the amplitudes of the fieldstrength corresponding to the minimum maintaining potentials at these frequencies, one sometimes gets values of the order of magnitude of ionizing or resonance potentials, sometimes values much lower. Thus, Rohde's observations on helium give, at the frequency 10^8, a minimum maintaining-potential of 11 volts between electrodes 19 mm. apart, therefore an oscillating fieldstrength of amplitude 5.8 (if there is no

[21] If v_0 is negative and algebraically less than $-eE/2\pi\nu m$, the energy of the electron is always *less* than, or at most equal to $1/2m(v_0^2 + v_n^2)$: the initial vis viva is also the greatest.

distortion by space-charge, another dubious assumption!). By the equation we derive 0.3 electron-volts for the maximum energy of those electrons for which $v_0 = 0$—a value barely more than one per cent of the resonance-potential of helium, the least amount which a normal helium atom can absorb as the first stage toward ionization! If we apply the equation to some of H. Gutton's results, the conclusions are equally startling; thus, putting 2 for E_v and $2 \cdot 10^7$ for ν (values observed with hydrogen in a tube 20 cm. long), we find 0.9 electron-volts for the maximum energy.

Were the discrepancies between these values of K_{mv} and the resonance-potentials of the gases somewhat smaller—were they, say, of the order of fifty per cent—they could readily be excused. Occasional electrons, for instance, might make collisions with atoms in just such ways and at just such times as to increase their accumulation of energy; thus, an electron which had started from rest ($v_0 = 0$) and had been speeded up to its utmost during the first half-cycle of the field and was about to be slowed down again, might have its velocity reversed by an elastic impact just at the end at that first half-cycle, so that the second half-cycle would speed it up still more (Hiedemann's idea). Or, occasional electrons might acquire a fund of energy in other ways, and have a considerable value of kinetic energy $(1/2)m(v_0^2 + v_n^2)$ at the instant $t = 0$; the form of the right-hand member of equation (28) now shows that the high-frequency field would augment their vis viva, not merely by the amount which we have just computed, but by an extra amount proportional to v_0. But a discrepancy of two orders of magnitude seems too large to be explained in such a way; and although it is impossible to make any positive affirmation, I suspect that there must be a permanent distortion of the field by space-charge, the mean value of the potential in the middle of the gas differing by several volts from its mean value near the electrodes—being presumably more positive, owing to an accumulation of positive ions.[22]

We ought now to compute the distance D through which a free electron moves in the high-frequency field, while its energy is mounting from zero (or the minimum value, whatever that may be) to the greatest value which it attains. For, if it should turn out that this distance is not more than a small fraction of the electronic mean-free-

[22] This is the condition in the direct-current "low-voltage arc" ("Electrical Phenomena in Gases," pp. 383–386) where the P.D. between anode and cathode is less than the resonance-potential of the gas, but the P.D. between a certain region of the gas on the one hand and the cathode on the other is at least as great as the resonance-potential. In the low-voltage arc the electrons are expelled from the cathode by heat independently applied, so that there is no need of a cathode-fall.

path in gases under the conditions of the actual experiments, then the foregoing theory would be vitiated at the start; electrons would seldom or never acquire the maximum amount of energy for which we have derived the general formula and which we have computed in certain special cases.

The distance D is described during a half-cycle of the high-frequency field, but the phase at which that half-cycle must be supposed to begin depends on v_0, which makes the problem intricate. If we put $v_0 = 0$, the electron starts from rest at $t = 0$ and attains its maximum speed at $t = 1/(2\nu)$, after traversing the distance given by the first of the following formulæ. If we put for v_0 the particular value which corresponds to an electron describing oscillations ahout a fixed centre, the doubled amplitude of these oscillations is what we want; it is given by the second formula:

$$\left.\begin{aligned} D &= \frac{1}{2\pi}\frac{e}{m}\frac{E}{\nu^2} = 2.81\cdot 10^{14}\left(\frac{E_v}{\nu^2}\right) \quad (v_0 = 0) \\ D &= \frac{1}{2\pi^2}\frac{e}{m}\frac{E}{\nu^2} = 8.95\cdot 10^{13}\left(\frac{E_v}{\nu^2}\right) \quad (v_0 = -\, eE/2\pi\nu m), \end{aligned}\right\} \qquad (33)$$

E_v standing as before for the amplitude of the fieldstrength in volts per centimeter.

The most which we can infer from these formulæ is, that when we find recorded a value of E_v (amplitude of the fieldstrength in the self-sustaining high-frequency glow) we should evaluate the product $10^{14}E_v/\nu^2$, and compare it with the electronic mean-free-path in the gas in question at the pressure in question; if it is much smaller than the electronic mean-free-path the foregoing theory is worth whatever can be got out of it; if it is much larger than the electronic mean-free-path the theory is worthless. For the two special cases (from Rohde and Gutton) for which I have just computed the values of K_{mv}, those of the product $10^{14}E_v/\nu^2$ come out as 0.06 cm. and 0.50 cm. respectively. The pressure of the gases (helium and hydrogen respectively) amounted in the two experiments to 0.400 and 0.001 mm. Hg respectively. Now the measurements of electronic mean-free-path for electrons of these speeds are imprecise and uncertain, and the concept itself is vague. The values which it is probably best to take are those derived by Townsend and his school from measurements of the diffusion of free electrons in gases.[23] That for hydrogen at .001 mm. Hg is so high (of the order of 40 cm.) that the theory is justified by an ample margin; that for helium at 0.4 mm. Hg (of the order of 0.1 mm.) is

[23] "Electrical Phenomena in Gases," pp. 248–252.

high enough to make it probable that electrons would often acquire the stated energy. But this is not to be taken as universally true for all the values of fieldstrength which have been observed in high-frequency glow-discharges.[24]

Certain data were obtained by Brasefield in experiments on air over a frequency-range extending downward from Kirchner's, and contained in Gutton's: that is to say, from $2 \cdot 10^7$ down to $1.25 \cdot 10^6$. The electrodes—external belts of metal wrapped around a tube of 4.5 cm. diameter—were no less than 40 cm. apart; and instead of measuring the least maintaining potential, Brasefield measured at various pressures the amplitude V of the voltage existing between the electrodes when a current of amplitude 100 mils was passing. The resulting V-vs-p curves for diverse frequencies had the customary form, concave-upward with single minima. As the frequency was raised from $1.25 \cdot 10^6$ to $1.5 \cdot 10^7$, the value of the minimum voltage and that of the pressure at which it was attained both trended downward, though with peculiar brief rises. As the frequency was further raised from $1.5 \cdot 10^7$ to $2 \cdot 10^7$, there was a sudden tremendous upswing of the minimum voltage, and a rise of the corresponding pressure,—anomalies recalling the singularities of Gutton's curves. Under the conditions prevailing at the minima of the curves for these two highest frequencies, there was agreement (within the wide limits of uncertainty) between K_{mv} and the ionizing-potential of hydrogen, and between D from the first of equations (33) and the electronic mean free path.

In the direct-current glow-discharges in a cylinder of gas contained in a tube, under certain conditions, there is a region (the so-called "positive column") throughout which the fieldstrength is uniform and low, and either decreases slowly as the current or the current-density is increased, or else remains sensibly the same. This region is apparently uniform in color and brightness. (I am not taking account of cases where it is "striated," or cases in which it is visibly dimmer near the wall than near the axis.) In the high-frequency glow-discharge there is also, under certain conditions, a region of uniform color and brightness occupying all of the tube except small portions near the electrodes. Townsend and his school undertook to measure the (alternating) fieldstrength in this region, and to compare it with the values obtained in the direct-current glow.

[24] If D computed by equations (33) should turn out to be very many times as great as the electronic mean-free-path, the proper procedure would be to compute the maximum energy of the oscillating electrons by the conventional method from the general equation (equation 5 of Part I) for electrons moving in dense gases. I fear, however, that in most cases the ratio of D to the electronic mean-free path is not great enough to allow of passing to this limiting case.

In the experiments (for instance those of Townsend and Nethercot) the distance l between the electrodes was varied, the current maintained at some constant value, the voltage plotted as function of l. The resulting V-vs-l curves were rising straight lines over large (but not unlimited) ranges of conditions. In these experiments the gases were nitrogen, helium and neon; the electrodes were external collars surrounding the tube, one of which could be shifted. The same result was later obtained by other pupils of Townsend (Hayman, P. Johnson, F. L. Jones), who sometimes worked with internal-electrode tubes, displacing one of the electrode-discs by a magnetic device.

This result suggests that in the main part of the glowing gas there is an alternating potential-gradient of constant amplitude, independent of l. Denote its amplitude [25] by b, those of current and voltage by i and V: we have

$$V = a + bl.$$

Now a is to be interpreted as the sum of potential drops across regions near the electrodes, where conditions differ from those of the middle of the glow.

Plotting V against l for various values of i, Townsend and Nethercot found this important fact: the slope of the line, the potential-gradient b, is independent of current over wide ranges (for instance, over the range of i from 3 to 18 mils, in nitrogen contained in a tube of diameter 3.9 cm.). The difference $(V - bl)$, however, increases with the current; over a certain range of current-strengths, the increase is linear. The value of the gradient b is of the order of a few volts per cm. Townsend and Nethercot give for nitrogen in a tube of 3.1 cm. diameter the values 13.2 (volts/cm.) at the pressure 0.26 mm. and 19.3 at the pressure 0.53 mm. For helium at 1 mm. they give 5.1; for neon at 1.06 mm. the value 3.5. These were obtained at the aforesaid frequencies of 7.5 and 4 millions; and so we meet the question of the dependence of b on frequency.

The value of b was found to be nearly independent of frequency, so far as the rather scanty measurements go; in nitrogen, the same for the frequencies $4 \cdot 10^6$ and $7.5 \cdot 10^6$ (Townsend and Nethercot); in helium and neon, constant over the range from $4.7 \cdot 10^5$ to $7.5 \cdot 10^6$ cycles (Hayman); in neon, by further experiments, constant over the range from $2.5 \cdot 10^6$ to 10^7 cycles (Johnson). This brings us to the question: how does b, which is the amplitude of the alternating potential-gradient in the high-frequency glow, compare with the

[25] Townsend's school give root-mean-square instead of amplitude-values for sinusoidal quantities.

constant gradient in the positive column of the direct-current discharge? A discharge of the latter type was set up in tubes (equipped with internal electrodes, of course) which had been employed for the high-frequency glow; the gradient in its positive column, measured by Townsend and Nethercot with nitrogen and by Johnson with neon, agreed fairly well with the value of $2b/\pi$ which is the *mean* value of the gradient in the discharge taken over any half-cycle. As for the term $(V - bl)$, which has been interpreted as the sum of potential-drops localized near the electrodes, it seems to vary inversely as the frequency over the limited ranges aforesaid.

To anyone desirous of penetrating through phenomena to fundamental laws, the situation as presented in this article must seem deplorable. The laws of the high-frequency discharge are almost purely empirical, either unexplained altogether, or explained only in a vague and qualitative way. Even the data do not form a complete or coherent system. For the remaining type of high-frequency glow not treated here—the so-called electrodeless discharge, in which high-frequency magnetic as well as electric fields pervade the ionized and excited gas—the situation is yet more obscure. Still, if the reader will consult again the article which preceded this one, he will be reminded that considerable progress has been made already in interpreting by fundamental theory the events which happen, when high-frequency fields are applied to gas which is independently ionized by other agents; and this gives hope of future success in extending the theory to the phenomena which occur when the high-frequency fields are themselves the causes of the ionization.

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Abstracts of Technical Articles from Bell System Sources

In January, 1932, a series of seven lectures by representatives of the Bell Telephone System was given before the Lowell Institute of Boston, Massachusetts. The general title of the series was "The Application of Science in Electrical Communication."

The lectures were as follows:

"Social Aspects of Communication Development," by Arthur W. Page, A.B., Vice President, American Telephone and Telegraph Company.

"An Introduction to Research in the Communication Field," by H. D. Arnold, Ph.D., Sc.D., Director of Research, Bell Telephone Laboratories.

"Researches in Speech and Hearing," by Harvey Fletcher, Ph.D., Acoustical Research Director, Bell Telephone Laboratories.

"Transoceanic Radio Telephony," by Ralph Bown, Ph.D., Department of Development and Research, American Telephone and Telegraph Company.

"Talking Motion Pictures and Other By-Products of Communication Research," by John E. Otterson, President, Electrical Research Products, Inc.

"Utilizing the Results of Fundamental Research in the Communication Field," by Frank B. Jewett, Ph.D., D.Sc., Vice President, American Telephone and Telegraph Company, President, Bell Telephone Laboratories.

"Picture Transmission and Television," by Herbert E. Ives, Ph.D., Sc.D., Electro-Optical Research Director, Bell Telephone Laboratories.

These lectures comprise a book entitled *Modern Communication* recently published by Houghton Mifflin Company, Boston and New York.

Three Superfluous Systems of Electromagnetic Units.[1] GEORGE A. CAMPBELL. At the present time the electromagnetic, electrostatic, Heaviside-Lorentz, practical and international systems of electric and magnetic units are used side by side in pure and applied electromagnetism. The question is here raised whether the use of this multiplicity of units should continue indefinitely into the future when

[1] *Physics*, November, 1932.

the conversion tables for translating from any system to any other system show the essential equivalence of all five systems. It is recommended that but one system be legalized and used generally in place of the five systems, and that this universal system be the coherent meter-kilogram-second-ohm or definitive system. It is further recommended that the international ohm be used in this system. This unit is the one actually used in exploring the physical world because laboratory resistances for physics and test room resistances for engineering have been so calibrated. Of far greater importance is the fact that by retaining the international ohm it will be simpler, and completely feasible, to eliminate what Heaviside called "that unmitigated nuisance, the 4π factor of the present B.A. units" from our preferred system of units.

A Compensated Thermionic Electrometer.[2] K. G. COMPTON and H. E. HARING. A compensated single tube electrometer is described and the principles of its operation discussed. This apparatus has been found to compare favorably with "balanced tube" circuits both as regards stability and sensitivity and to be superior in many respects to the quadrant electrometers which usually have been used for the measurement of small currents, high resistance, or of voltage in circuits of high resistance and in those cases where only an infinitesimal current may be drawn from the source of the electromotive force. For most measurements the degree of compensation afforded has been found to be sufficient to make possible the use of dry cells or even properly controlled rectified alternating current as a power source.

Combined Reverberation Time of Electrically Coupled Rooms.[3] A. P. HILL. The importance of controlling the reverberation time of auditoriums, music rooms, etc., is well recognized, and curves showing the optimum reverberation times for buildings of different volumes have been drawn and have attained general acceptance. In the recording and reproduction of sound for talking motion pictures, however, the reverberation problem is somewhat more complex than is the case for rooms in which sound is originally produced, due to the fact that there are three factors to deal with: first, the reverberation time of the space in which the sound is recorded; second, that of the space in which it is reproduced; third, the resultant reverberation time produced by electrically coupling these two spaces together. This is, of course, done in actual practice. This paper deals with the

[2] *Electrochemical Society Preprint* 62–17.

[3] *Jour. Acous. Soc. Amer.*, July, 1932.

third factor and presents theoretical and experimental data showing how this resultant reverberation time may be determined. It is a matter on which little information has been available up to the present time.

Air-Conditioning System for Low Humidities Required During the Manufacture of Telephone Cables.[4] F. H. KRUGER. This paper considers the requirements of an air-conditioning system to maintain the necessary humidities and temperatures in the cable storage rooms. The selection, design and performance of a combined refrigeration and moisture adsorption system are described. A two-stage refrigeration system cools and consequently drys the air which is delivered to the adsorption system and to the loop cable storage room for the removal of heat. The adsorption system supplies air of a low moisture content to the toll cable storage room. Air recirculated from the toll room maintains the correct humidities in the loop cable storage room. Silica gel placed in two beds or adsorbers dehydrates the air passing through the adsorption system. An air heater and cooler are successively used to condition the moistened gel in the adsorbers alternately. Finally the distribution of air and the humidity determinations in the storage rooms are discussed.

Photo-conductivity.[5] FOSTER C. NIX. The influence of light on the flow of current through certain solids had been observed for several decades, but without important results prior to the brilliant work of Gudden, Pohl, and their collaborators. These investigators made the important advance of passing from the study of polycrystalline semiconductors having comparatively large conductivities, when not illuminated, over to single crystals of insulators. This enabled them to study the conductivity arising when the crystal is irradiated with light of suitable wave-length under simpler and more controllable conditions than had hitherto been obtainable. In many cases they were able, by using feeble light and low voltages, to distinguish between phenomena which they called "primary" or "secondary." The distinction is fundamental and is treated at length in this article. The article begins with an account of the phenomenon designated by Gudden and Pohl as primary and sometimes classified under the name *internal photoelectric effect* to distinguish it from the so-called external photoelectric effect (i.e., ejection of electrons from substances into surrounding gas or vacuum by incident light). The secondary phenomena are then taken up: first in cases where they coexist with

[4] *Heating, Piping and Air Conditioning,* November, 1932.
[5] *Reviews of Modern Physics,* October, 1932.

primary, then in cases where they are observed alone. In the closing section are discussed the cases in which electromotive forces are generated in solids by light.

An Estimate of the Frequency Distribution of Atmospheric Noise.[6] R. K. Potter. A relation between atmospheric noise intensity and frequency is estimated upon the basis of noise measurement data covering the frequency range between 15 and 60 kilocycles, and 2 and 20 megacycles.

[6] *Proc. I. R. E.*, September, 1932.